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REVIEW

Ecological economics as the science of sustainability and transformation: Integrating entropy, sustainable scale, and justice

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Abstract

Ecological economics, developed in the late 1980s, came to be known as the multi- and transdisciplinary science of sustainability. Since that time, it has blended basic and applied research with the intention of both informing and bringing change to environmental policy, governance, and society. However, many conventional economists have questioned its originality and contributions. This paper begins by clarifying the foundational perspectives of ecological economics that it engages an economy embedded in both real and limited ecosystems as well as socially constructed power relations. Herman Daly, a founder of the field, expanded on Nicholas Georgescu-Roegen's *entropy economics* by focusing on a quantifiable sustainable *scale* of the economy and achieving *justice* in the control and distribution of economic benefits. He called for both quantitative analyses of economic scale and discursive approaches to a just distribution. The paper then discusses how the terms entropy, scale, and justice are used and interact in the literature, illustrated by some of the key debates in the field involving the Ecological Footprint, substitutability of natural and manufactured capital, and the growth—"agrowth"—degrowth debate. The debates also illustrate the potential for the field to influence policy. Ecological economics as the science of both sustainability and transformation can deploy numerous concepts and tools to provide insights on how to illuminate and solve some of the most pressing problems of the Anthropocene.

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1. Introduction

Ecological economics emerged in the late 1980s as the science of sustainability [1–5]. Universal definitions of ecological economics have been recognized, but challenges remain in advancing a consistent, integrated conceptualization of the field. Providing an extensive definition for the *Dictionary of Ecological Economics* [6], Herman Daly characterizes ecological economics as [7]:

> The view that the macroeconomy is a subsystem of the ecosphere that is sustained by a metabolic throughput of matter-energy beginning with depletion of the finite ecosphere's low

entropy resources and ending with its pollution by resulting high entropy wastes. The economy recycles materials to varying extents; energy cannot be recycled. The containing ecosphere is materially closed and its biogeochemical cycles, powered by the Sun, recirculate materials.

(. . .) Ecological economics focuses first on the scale of the economy relative to the ecosphere (is it sustainable?); second on the distribution of resources among people (is it just?); and third on the allocation of resources among alternative uses (is it efficient?). . ..

Daly's third focus, efficiency, is a direct link to conventional (neoclassical) economics, which places efficiency at the top of its agenda. Achieving efficiency attempts to realize the normative goal of maximizing social welfare. However, this bridge between the 2 fields has contributed to a belief that there is little if any difference between ecological and conventional economics. Pezzey and Toman provide a compendium of key writings on the emergence of sustainability as a topic in economics, many of which display strong neoclassical influences [8]. Others push further, arguing that ecological economics has yet to provide a widely accepted, viable alternative to the shortcomings of conventional economics [9–11]. Thus, it is important that the key distinguishing themes identified by Daly, Nicholas Georgescu-Roegen, and others, namely entropy, sustainable scale, and justice (Fig 1), be clearly justified, explained, interrelated, and integrated to help strengthen the core tenets of the field [1,12]. While economic efficiency is included in Daly's definition, it plays the role of providing useful guidance once the foundations of physical-material sustainability and justice have been achieved through policy, and is not emphasized here.

Ecological economics has developed with competing schools of thought and methodological pluralism. It is an interdisciplinary research field, ranging from a close alignment with environmental and resource economics to heterodox and even radical social ecological economics approaches [10,13–15]. Representative debates (Table 1) including the merits of Ecological Footprint analysis, the possibility and extent of substituting manufactured capital for natural

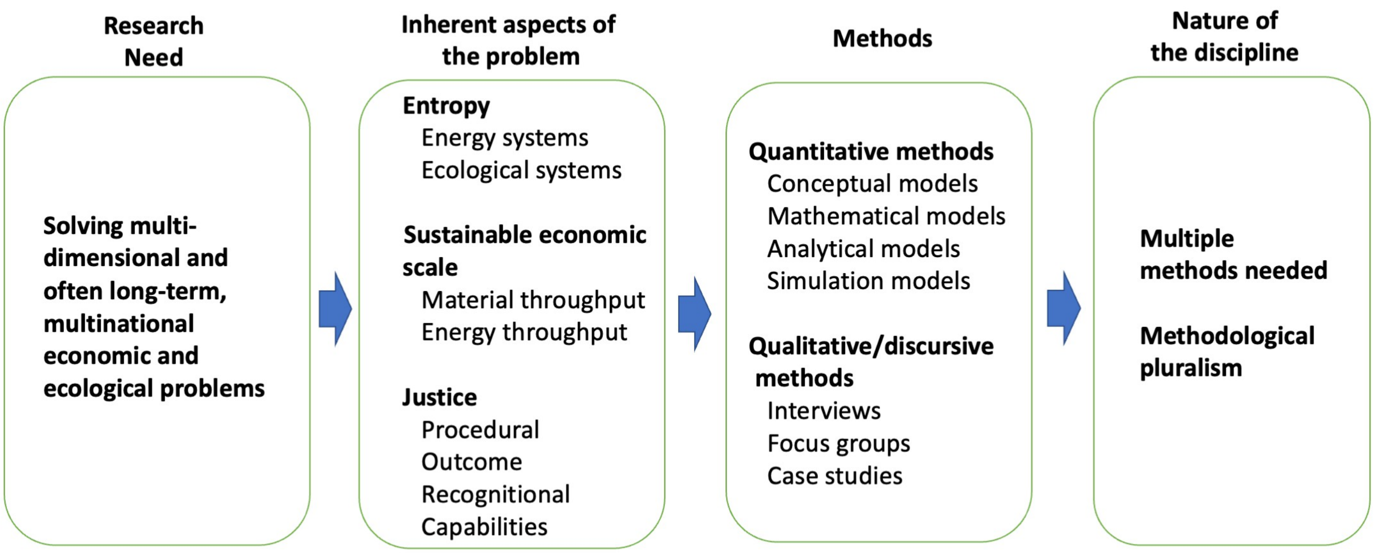

Fig 1. Ecological economics: How the nature of its research questions determines the nature of the research discipline. In order to address problems with combined economic and ecological elements (box 1, left-to-right), a framing related to entropic forces, impacts of economic scale, and elements of justice is needed (box 2). This framing calls for numerous methods of research depending on what aspect of the problem is under particular scrutiny (box 3). In the case of ecological economics, an accommodation of multiple methods is required (box 4).

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Table 1. Debates in ecological economics.

Topic	Debate	Links to sustainability and transformation	Citations
Ecological Footprint analysis	Is it possible to accurately measure a region's consumption of biological regenerative capacity in comparison to its regenerative capacity?	Could identify "overshoot" and move policy toward greater protection of essential natural systems.	50–52,87–97
Substitution of engineered capital for natural capital	To what extent can human innovation find replacements for essential natural systems, such as pollination, topsoil regeneration, and water purification?	Identifying natural resources and systems with weak or no substitutability can focus preservation efforts and critical natural capital.	28,36–37,71–76,100
The merits of economic growth as a measure of social well-being	Is pursuit of economic growth is too damaging to natural systems, and if so, do the concepts of degrowth or a-growth (abandoning the concept completely) provide useful alternative perspectives?	Could profoundly alter the goals of economic policy toward protection of the most vulnerable.	61–67,105–109
Valuing nature in financial units	Is it meaningful to place a finite numerical financial value on essential natural life-support systems, and if so, can an accurate number be determined?	Could render more accurate the results of benefit-cost analysis, a commonly used tool of policy analysis and project selection.	18–21
Circular economy as a policy goal	Do the merits of reducing the economy's material throughput justify the disruption it would cause?	Could trigger macroeconomic precautionary actions to protect public health, infrastructure, and the economy.	16,17
Rapid energy transition	Should the existing fossil-fuel infrastructure be abandoned before the end of its useful lifetime and be replaced with renewable energy?	Could reduce the overall, long-term adverse impacts of climate change.	51–62

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capital, and the value of agrowth/degrowth perspectives, are illustrated later in this paper. Other debates include whether and how to measure nature in financial terms, whether to accelerate the transition from fossil to renewable energy sources, and the importance of pursuing a circular economy [16–21]. Methodologically, the field includes both discursive/expositive and quantitative/model-oriented branches. Yet, even these different approaches to research are anchored in Daly's vision and thus all emerge from the same foundational concepts.

This paper discussions how research in ecological economics can provide guidance for policy transformation necessary to achieving a sustainable future and suggests the addition of "and transformation" to its historical description as the "science of sustainability."

The paper has 4 sections. We first provide definitions and discussions of the central concepts and themes of entropy, sustainable scale, and justice, followed by discussion of linkages between these 3 pillars. Following this, we present 3 of many current debates in ecological economics that both distinguish the field from neoclassical economics and demonstrate the importance and difficulty of integrating entropy, justice, and sustainable economic scale, but from which tools for a sustainability future can be developed. Ecological economics can help researchers to more effectively design policies and interventions to accomplish a sustainable transition. The paper closes by revisiting methodological pluralism (itself another debate in the field), suggesting that multiple methods are inevitable when research is placed in a context of entropic forces, justice, and sustainable economic scale, as well as when a discipline spans from basic to applied research.

2. Three foundational themes of ecological economics

Here, we briefly examine the 3 major foundational themes of ecological economics, emerging from thermodynamics, ecology, and ethics.

2.1. Entropy

Entropy is concerned with levels of disorder, ignorance, and irreversible change. Entropy-as-ignorance is found primarily in information theory, while entropy as disorder and irreversible change are utilized more widely [22], including in ecological economics. It can be measured as energy transformations and transfers within a closed system [23].

2.1.1. Entropy as disorder. With respect to disorder, the greater the organization of a system, the lower its entropy. Conversely, the greater the disorder, the higher its entropy. A low-entropy state is almost always preferred to a high-entropy state because the system has greater potential use and productivity. For example:

- An intact primary forest has the resilience to resist and overcome diseases, droughts, fires, and other disturbances while maintaining its species diversity and other characteristics. This is due to an organization of biotic and abiotic resources that has emerged over centuries. Interventions in the forest such as clearcutting, hunting species to extinction, introducing exotic species, and removing water resources reduce the ability of the forest to respond and adapt. When a low-entropy primary forest has had resources removed for other uses, simplifying what remains, its entropy increases.

The highest measure of entropy is when a system is no longer capable of doing any work. A library reduced to ashes by a fire would be an example. That is a higher level of entropy than books spilled on the floor because in the latter case they can still be replaced on the shelves, and the library can continue to function.

Carnot's pioneering insight about entropy is that it will not go down by itself, meaning no system will become more organized and capable of providing work/benefits in isolation [24]. An external source of energy is needed. For example:

- The disturbed forest needs sunlight (and other inputs) to drive biotic processes of recovery.
- The library needs the effort of librarians to restack its books.

In each case, action (and energy) is needed to reduce the disturbed system's entropy. Sunlight is a source of high-quality energy for the forest, while librarians burn chemical energy as they carry out their activities.

2.1.2. Entropy and economic activity. The economy is a system. Physically, the economy involves the organized movement of physical materials and large quantities of energy. Georgescu-Roegen's seminal contribution to economics was the recognition that economic activity, the purpose of which is to improve people's lives, inevitably exacts a cost [12,25–28]. Nothing gets better in isolation. If the economy improves quality of life, such as providing new homes for first-time home buyers, it might seem locally like an overall improvement, but at a larger scale it took more energy entering the economy to build them than the finished homes embody. Economic activity always operates at a net entropic gain. Inputs of energy and materials will be greater than beneficial outputs because of unavoidable side streams of waste heat, bent nails, sawdust, spilled paint, workplace injuries, and other inefficiencies. Even though equilibrium is a core concept in economic analysis, there can only be temporary equilibria in subsystems. The overall system will never equilibrate and will constantly require additional inputs.

2.2. Sustainable scale of the macroeconomy

Sustainable scale describes an economy that can adapt to entropic forces and maintain peoples' quality of life through many future generations, or, more succinctly, achieve non-declining human well-being over time [29,30]. This is a clear principle. An ongoing research challenge includes how to measure economic activity in order to learn if a sustainable scale has been achieved and what must be done to achieve/maintain it.

How one defines sustainability points to the variables one chooses to examine whether an economy is on a sustainable path, and some definitions may also render quantification all but impossible. As a first step to generating measurable criteria, it is important to delineate categories of importance to sustainable economic development [31]. These include intergenerational and intragenerational social equity or justice, the conservation of biodiversity and ecosystem integrity, the Precautionary Principle, community participation in decision-making, and improvement of individual and community well-being. These categories can be broken down into both quantifiable and descriptive components, with biological criteria being the most developed.

Minimizing and in some cases forgoing the flow of physical materials that pass through the economy can help reduce the scale of the economy. Ecological economics has contributed to our understanding of material flow. Material flow analysis (MFA) quantifies stocks and flows of materials mobilized by economic processes, for example, using tonnes of material as a measurement unit [32]. MFA studies domestic extraction and trade of materials, wastes, and emissions in one empirical framework, and can be applied at multiple scales, from countries and regions [33] to cities [34]. MFA methods are broadly agreed upon [35].

Materials are mobilized from a base of natural capital. Ecological economists have engaged the question of how one shares finite natural capital, such as helium reserves, across near-infinite future human generations. One framework that has emerged includes protecting "critical" natural capital to ensure strong sustainability [36], while also using the benefits of natural capital consumption to search for a substitute to what is being used up.

Ultimately, sustainable scale can be seen as the highest level of material throughput that can occur through time, based on biophysical limits [37,38]. Sustainable scale often is found at the level of economic throughput that is identical to the regeneration rate of ecosystems affected by the throughput. Throughput, in turn, can be defined as an entropic process describing Earth's anthropogenic metabolic flow. It refers to objects that travel through the human sphere, entering as (low entropy) resources (or natural capital), such as wood, coal, and metals, and exiting as (high entropy) waste to air, land, and water [39]. Any further increase in throughput beyond this scale is unsustainable. Ensuring a sustainable scale requires observing 3 rules [40]: (a) we harvest renewable resources below the natural regeneration rates of all critical ecosystem services associated with the specific throughput activities; (b) we maintain our rate of throughput so that their emissions or wastes do not exceed the rates that can be absorbed or broken down by natural processes in a meaningful time span; and (c) any use of nonrenewable resources should be coupled with investment in replacing the nonrenewable resource with renewable alternatives or coupling the nonrenewable usage with a renewable offset.

2.3. Justice

Justice encompasses a set of normative perspectives on human relationships in the pursuit of a more equitable and fair society, and is thus socially constructed. Four aspects of justice can be considered—distributional, procedural, recognitional, as well as human capabilities [41] (Table 2).

Table 2. Four perspectives on justice.

Perspective	Summary	Citations
Distributional	Measures fairness in terms of the outcomes of resource allocation.	41,43
Procedural	Measures fairness in terms of stakeholders' access to and participation in resource allocation decisions.	43
Recognitional	Measures fairness in terms of whether and how the most vulnerable are brought into decision processes.	42,43
Capacity	Focuses more broadly than allocation processes to include all aspects of life and the ability to lead a valuable, meaningful life.	41,44–46

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Distributional justice focuses on fairness with respect to the outcomes of resource allocation. It hinges on a definition of what is considered fair, which can take into consideration many perspectives. Examples include the types and intensity of needs, prior rights and patterns of use, equity, overall scarcity and substitutes, and community expectations. The distributional focus is on the outcome of an allocation event or pattern and whether it meets the conception of justice applied to the event or pattern.

Procedural justice focuses on the processes that result in resource allocation decisions. A just procedure provides access on relatively equal footing to the decision process for all who are directly involved and affected. For example, all parties should have ready access to documentation and the right to make presentations to decision-makers. Access could include affordable availability of expertise resources, so all parties involved have an equal opportunity to understand the issues and make informed arguments. Other factors include providing sufficient time and locational access to enable meaningful participation.

Recognitional justice relates to gathering input on a pending decision. It emphasizes the importance of directly including marginalized and underrepresented communities to state their own perspectives on potential harms and risks from a resource allocation. John Rawls provides a classic moral argument for recognitional justice by posing the thought exercise of how a group would go about making an allocation decision, and what allocation they would ultimately reach, if no one in the group knew their relative political, social, and economic standing compared to others [42]. The risk of finding out that one is the poorest and/or least represented would compel participants to choose an allocation that would involve and provide for all people.

Distributional, procedural, and recognitional justice are common subcategories of Justice, sometimes termed the "Three-Tenet Framework" [43]. A fourth perspective focuses on capabilities. Cousins describes this conception of justice as "providing the means and mechanisms for people to be able to live valuable and meaningful lives" [41,44,45]. Here, a capability is an activity, opportunity, or right that can truly be exercised by an individual. No hindrances or impediments block its pursuit. Examples include securing fresh water for domestic use and getting an education. In addition, "being" can be considered to include personal attributes (e.g., lack of hunger) that enable someone to function well in society, and, "doing" as having access to procedures and activities the help someone lead a good and meaningful life, are the 2 key elements of capabilities-oriented justice [46]. A just society provides its members with capabilities, leaving the choice to pursue them up to the individual. Capabilities, if pursued, provide the foundation of a meaningful life. Capabilities are also made available in a context of preserving the ability to continue to provide them into the future.

3. Integrating the foundational concepts

Building a discipline from conceptual foundations calls for identifying how the foundations connect to each other in ways that provide new paths of inquiry. Here, we draw connections between entropy, sustainable scale, and justice as 3 pairs of ideas. Although certainly not exhaustive, a wide range of topics of global importance that are regularly addressed by ecological economists emerge from the discussion.

3.1. Connecting entropy with a sustainable scale

As a fundamental and immutable biophysical process, entropy has a myriad of critical effects on the economy and any hope for achieving a sustainable scale. The massive use of minerals, materials, and nonrenewable fossil fuels that has accompanied economic growth since the Industrial Revolution is captured in the transition from an "empty world" economy to a "full world" economy today (Fig 2). The large and accelerating entropic nature of the economic system is manifested in environmental pollutants, wastes, destruction of natural capital, declining ecosystem services, and dangerous buildup of greenhouse gases [47]. It is well known that current energy and material pathways are unsustainable. Sustainable mining, for example, is conceptually impossible and calls for such actually focus on lowering environmental impacts and burdens, not achieving a sustainable state [48].

One way to track progress toward a sustainable scale is by using material footprint and carbon footprint accounting. A material footprint is a metric of the material requirements of final demand of a country and serves as a proxy for the overall environmental pressure and impact caused by household and government consumption and capital investment [49]. The metric is established by measuring the raw material equivalent (RME) of traded materials and commodities as RME of imports + domestic extraction–RME of exports. One arrives at RME by calculating all upstream and downstream material requirements of final demand. The most common method for the attribution of material extraction to final demand is by environmentally extended input–output analysis using a global multiregional input–output (MRIO) table.

Alternatively, life-cycle assessment and hybrid methods can be used [50]. There are physical limits to potential improvements in process efficiency in the production of several major categories of materials. Further, scale constraints at the macroeconomic level cannot be defined as easily and explicitly as for individual sectors. This is because thermodynamic efficiency constraints imposed on production processes may mean little for an industry since firms can substitute to alternative production processes to avoid them [28].

A carbon footprint, in turn, is the total carbon dioxide (CO_2), CO_2+methane, or greenhouse gas emissions of a person, firm, city, region, country, activity, or system over a given period or life cycle [51]. Non-CO_2 emissions are usually calculated as CO_2–equivalencies based on each gas's relevant 100-year global warming potential [52]. CO_2 production is a prime example of entropic waste when energy is produced using fossil fuels.

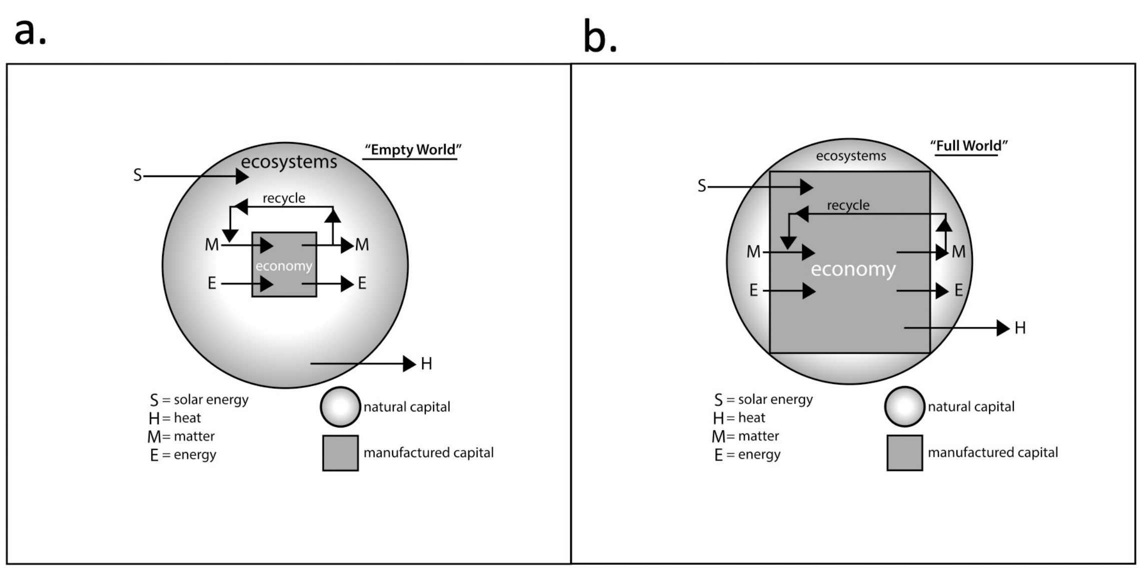

Fig 2. Herman Daly's classic depiction of a world in which matter and energy enter and leave the economy and are recycled by ecosystems. A small economy (an "empty world") relative to the capacity of natural systems to process waste energy and matter (left side) is compared to a "full world" economy too large for ecosystem processes to process the economy's waste (right side). Some recycling still occurs in the full world involving both natural and human-made systems, but natural capital is drawn down more rapidly than in an empty-world scenario. The Earth system is closed except for entering sunlight and departing heat. Drawn by Jill Gotschalk.

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The achievement of substantially reduced material and carbon footprints will require an energy transition, perhaps even an energy revolution. An energy transition is a long-term structural change in energy systems, typically in a nation-state [53] or globally [54]. In the 21st century, many political regimes have promoted a planned energy transition and decarbonization to stay within the Earth's carrying capacity by requiring or incentivizing greater use of renewable-flow and therefore sustainable energy sources [55,56]. An energy revolution would include a massive and rapid energy transition to renewable sources, much greater efficiency in the use of energy [57], while addressing the social dislocation of workers and communities that would occur during the transition [58]. Many analysts have called for greater use of nuclear power to combat climate change through rapid decarbonization of the energy system, but this pathway remains controversial [59–61]. One must consider the unresolved problems of nuclear weapons proliferation, regional environmental threats if nuclear power plants are damaged, and long-term waste disposal. Assuming these challenges can be addressed, energy plans and projections suggest that nuclear power will not be a major part of a sustainable energy transition, at least through the middle of the 21st century [62].

Given the great challenges in achieving a sustainable scale, many ecological economists have called for degrowth, though by how much is debated, as discussed below. Degrowth is a process of radical political and economic reorganization leading to drastically reduced resource and energy use while still improving quality of life. The degrowth hypothesis is that it is possible to organize a material and energy transition yet still live well under a different, post-capitalist political-economic system that has a radically smaller resource throughput [63]. Degrowth is a reincarnation of older limits-to-growth ideas. These emerged in France in the 1990s, partly inspired from the translation of works of Georgescu-Roegen. Andre Gorz was the first to launch the term in French in 1972, in a debate concerning the Club of Rome's famous report [64]. Compared to limits-to-growth arguments, or steady-state economics, the degrowth literature has a stronger emphasis on autonomy, conviviality, and the desirability of collective self-limitation [65]. It also includes a critique of capitalism as an exploitative system that can only grow or collapse, and that therefore must be opposed and replaced [66,67]. Degrowth, the argument goes, is necessary because "green growth" is impossible due to entropic limits to substitutability and decoupling [68], and because continuous growth is a source of unsustainable extraction and exploitation of environments at the world's commodity frontiers.

3.2. Connecting sustainable scale and justice

A useful framing of the topic of sustainability and justice considers current generations, future generations, and the natural world [69]. Limiting impacts on the natural world by curtailing economic growth to a sustainable level has major implications for justice. Impacts have been described by Daly and Farley ([70], pp. 12–13). For example, the excessive use of fossil fuels and other natural resources today will have negative effects for future generations because of the harmful effects of climate change, as well as growing resource scarcities [71]. An example of an impacted resource is dry-period water runoff from melting glaciers, a process threatened by climatic warming. While substitutes will emerge, they may be limited and of lower quality. In addition, there are already significant injustices even at the current global rates of resource consumption, with over 1 billion people living in poverty.

Conventional views of sustainable development, such as Solow sustainability and weak sustainability, address the challenge of achieving a sustainable scale of the economy with justice in unsatisfactory ways. For example, Solow sustainability, named after neoclassical economist Robert Solow, promotes the possibility of maintaining or increasing the intertemporal level of consumption, a proxy for human well-being, by substituting manufactured capital for natural resources, which are assumed to be very close substitutes [72,73]. This kind of substitution is formalized in a growth model based on an aggregate production function. The substitution mechanism involves changes in the composition of output, the type of resources, or the technologies used to transform them. It all hinges on a questionable assumption that there are manufactured substitutes for natural resources that don't themselves depend on natural resources to be produced [74]. In the case of using other natural resources, there is no requirement that they be sustainably harvested.

Similarly, weak sustainability uses a common unit of measurement to emphasize the substitutability of natural and manufactured capital, while strong sustainability measures natural and manufactured capital separately [75,76]. From a weak sustainability perspective, growing the overall economy via ever-increasing throughput remains an option. No longer pursuing the goal of growth, such as pursuing degrowth instead, would foreclose the option of addressing wealth injustice by growing the economy, something that ecological economics consider to be an unsuccessful approach in any event. It has been argued, for example, that degrowth is necessary because continuous economic growth is a source of global injustice [63]. It causes unsustainable extraction and exploitation of people living and working in the world's commodity-production industries [77]. Even though economic growth has in recent decades been higher within the most populous developing countries, such as India and China, it has been associated with growing income inequality [78,79]. However, international income inequality actually declined in recent years both before and during the Coronavirus-19 pandemic [80], indicating that a just process of degrowth to achieve sustainable economic scale can be achieved.

Sustainable scale is also influenced by stochastic factors such as major industrial accidents, pandemics, and wars, which in turn affect both intragenerational and intergenerational justice. The recent Coronavirus-19 pandemic temporarily halted global economic growth, caused a recession, and led to calls for major economic reforms [81,82]. Similarly, the Russian invasion and war in Ukraine since 2022 disrupted global fossil fuel supplies and led to North American and European countries reducing or phasing out the import and use of Russia's substantial oil and gas resources, thereby accelerating the movement toward substitutes, including more sustainable energy options [83]. These actions help to lower the global dependence on fossil fuels while simultaneously decreasing the inequities of existing consumption patterns. Conversely, the war also delayed grain exports from Ukraine, which disproportionately harmed poorer, food-import-dependent nations more than wealthier ones.

3.3. Connecting justice and entropy

The entropy concept reminds us that pollution is an inevitable result of economic activity [47]. Humans do, however, have some control over where pollution occurs, what forms it takes, how much is generated, and who is impacted by it. Clearer understandings of justice offer structured paths of analysis of pollution reduction and management [84]. Likewise, the Precautionary Principle offers an intergenerational justice-based perspective on what economic activities should be foregone to reduce potential harmful side-effects [85,86].

Similar to economic scale debates, one can define a condition for intergenerational justice as a distribution that does not increase entropy faster than Earth systems-plus-sunlight can reduce it. This places a theoretical cap on mobilization and consumption of natural capital. Distributional implications include how much is mobilized and utilized in today's economy, and by whom, as well as how much is preserved for future generations, similar to no-growth and degrowth perspectives. More broadly, entropy reduces the possibility that distributional justice issues can be avoided altogether (a possibility under weak sustainability) by continuously growing the overall economy even if its distribution of benefits is unjust. Since entropy-based arguments push in the direction of limiting use of natural capital, both inter- and intragenerational justice issues become more acute.

Procedural and recognitional justice connect with entropy because it is both necessary and difficult to identify how much less should be consumed to preserve entropy-reducing large-scale life-support systems. The process of identifying a mix of natural resources and the maximum amounts that should be consumed will gain legitimacy and additional accuracy from processes that emerge from procedural justice principles, such as the inclusion of diverse stakeholder perspectives.

4. Key debates in ecological economics

This section further discusses some directions taken, and debated, in ecological economics. Each topic has been raised earlier as exemplars of the integration of core concepts in the field and can inform policy interventions to help promote a sustainable society. A common theme of these examples is the need to measure, understand, and respect the sustainable scale of the macroeconomy. These debates include using ecological footprinting at the national or state/provincial level as a method of comparing regional consumption to ecological limits, whether and the extent to which we can innovate our way out of ecological scarcity through human ingenuity (known as the substitutability debate), and how to move on from the ecologically damaging focus on growth as a macroeconomic and social goal.

4.1. Ecological footprinting

Ecological footprinting emerges from Daly's insights into the sustainable scale of the economy. It offers an empirical approach to measuring how much of the Earth's regenerative capacity is needed to accomplish specific economic tasks. Ecological footprinting is a diagnostic tool that generates measurements of the extent to which today's economic activity is within sustainable limits or is in unsustainable "overshoot" [87]. By generating a regionally comparable indicator of consumption of ecological capacity, ecological footprint analysis can also provide data inputs to debates on environmental justice, depending on the geographic scale of the analysis [88–89].

Originated by William Rees [90] and developed with his then-graduate student Mathis Wackernagel [91], 2 measures are calculated and compared. The first is called biocapacity, an area's renewable bioproductivity, or its ability to absorb the waste products of the economy. Biocapacity can be measured for a region or, using equivalence factors, the entire Earth. The second measure totals consumed resources within an area over a year's time. This latter measure, typically in hectares or acres, is called the Ecological Footprint. The ratio of biocapacity to Ecological Footprint provides a single-unit descriptor of reserves (greater than one), equilibrium (equals one), or deficit (less than one) in a region's capacity to sustain the existing economy.

The Ecological Footprint approach and tool have been subject to substantial debate and criticism. One of the strengths of the Ecological Footprint—that it provides a single measure that summarizes a region's current state of ecological sustainability—also presents a weakness in the large number of assumptions and input choices needed to generate equivalencies. The single measure includes assessments of demands on oceans, farmland, forests, and other lands. Some have argued that too many judgments and estimations are needed for the resulting number to retain meaning [92,93].

Another critique [94] challenges the methodology's finding that only carbon sequestration capacity is far surpassed on a global level, while other major categories of global resources consumption, including cropland and fishing grounds, have remained in equilibrium or retained some reserve capacity. This, it is argued, understates pressures on fisheries, topsoil losses, threats to irrigation water supply, and other growing ecological stresses. The critique also notes that the footprint methodology accepts achieving carbon neutrality through the massive planting of monoculture forests, a policy action that few ecologists and land-use planners would recommend. A related critique [95] noted that forest carbon sinks eventually reach capacity and can no longer store new carbon in living biomass, a dynamic the per-hectare metric of biocapacity doesn't capture.

Footprint advocates [96] have responded that national level studies offer clear and insightful differences in performance among the categories of resource consumption. In terms of the acceptability of monoculture afforestation, the existence of one possible but unrealistic remediation scenario should not nullify the tool's ability to inform more realistic alternatives. And with respect to the declining nature of carbon sink capacity as forests mature, advocates respond that a global average forest carbon sequestration rate is used [97]. We note that this may still overestimate the potential for forest carbon sequestration to counterbalance greenhouse gas emissions because successful carbon-sequestration forest sites have already absorbed a significant amount of their carbon sequestration capacity—otherwise they wouldn't be considered successes. Existing carbon sequestration sites may therefore now be comparable to lower-than-average potential sites for additional carbon sequestration. The estimated global average per hectare available capacity for carbon sequestration may therefore be higher than the actual performance that is located largely on plots with reduced capacity. Nevertheless, the fundamental purpose of footprint accounting, to estimate human demand for biocapacity and the finding that most countries are in ecological deficit, has been shown to be robust [96].

4.2. Natural capital and its substitutability

The term *natural capital* was coined by E.F. Shumacher [98] and first explored in ecological economics by Robert Costanza with Daly [18]. Daly [99] defends the concept against arguments that the framing of natural systems as forms of capital conceptually pulls essential life-supporting systems into a market framework that could lead to its treatment like other market goods and its depletion and destruction. He points out that first recognizing nature as a source of value is essential to properly allocating it through public policy, which could include the judicious use of markets.

An ongoing debate concerns the extent to which natural capital can be substituted for manufactured (also called built, physical, produced, or human-made) capital. Examples abound of substitutions—ranging from gasoline-powered transportation being supplanted by electric vehicles to artificial materials replacing actual skins and furs in the clothing industry. After almost 3 decades of critical evaluation of the extent to which we can draw down or erode seemingly essential systems, such as pollination services, fertile soils, and climate regulation, and trust human-developed alternatives to maintain the benefits provided by the service, the debate has been largely settled. In a recent review, it was concluded that Daly's position that substitutability between natural capital and labor or manufactured capital is low is largely correct, meaning a sustainable future requires strong policy involvement to protect critical natural capital (CNC) [100].

The policy intervention in this case involves the protection of CNC, which are forms of natural capital that provide life-support functions, improve human welfare, but are difficult or impossible to substitute for [101]. Ecological economists acknowledge that we unfortunately may not always know what elements of natural capital are critical, and the valuation of natural capital that may be approaching critical but uncertain limits is extremely difficult to perform

[102]. Examples of CNC may include the Amazon rainforest, freshwater supply, fertile topsoil, and biodiversity.

Federal natural resources policy in the United States has historically focused on protecting endangered and threatened species and their habitat, though funding resources are typically very limited. In addition, significant public lands are set aside and have some protections, especially in US western states, though the public land designation has little to do with the inherent value of natural capital on such lands. The protection of CNC would require ecological analyses to determine the value of natural capital and its subsequent protection. Non-government organizations such as The Nature Conservancy and other land trusts generally do a better job of determining the uniqueness of lands that they protect and often work with government agencies, but much more can be done. A notable exception for the US government was the establishment and expansion in the Northwestern Hawaiian Islands in 2006 and 2016 of the no-take zone marine protected area, the 1.5 million kilometer^2 Papahānaumokuākea Marine National Monument, due to its critical value as a pristine coral reef ecosystem [103].

4.3. Economic growth, degrowth, or agrowth: Reducing material throughput while achieving economic and social justice

An emphasis in ecological economics from its inception has been criticism of the ill-advised priority given to economic growth as a measure of societal well-being, in light of the biophysical limits of the planet. These concerns date back to Daly's promotion of the steady-state economy in the 1970s [104] and the widely recognized shortcomings of economic growth metrics such as gross domestic product as an imprecise and misleading indicator of social welfare or progress [105]. Moreover, as noted earlier, entropy reduces the possibility that distributional justice issues can be avoided altogether by continuously growing the macroeconomy even if the current distribution of economic benefits is unjust.

In an extension of the limits to growth debates from the 1970s [64], many scholars in ecological economics have called for degrowth as an alternative. Degrowth was inspired by Georgescu-Roegen's work on entropy and the economic process, which argued that economic scarcity is rooted in a biophysical reality [12]. The degrowth hypothesis, discussed earlier, goes beyond the steady-state perspective and proposes that it is possible, indeed essential, to live well under a different political-economic system with a much smaller and sustainable throughput of material resources and energy [63]. However, while degrowth may be desirable from a sustainability perspective, its practical interpretation can be ambiguous, and it seems naïve to expect collective self-limitation from economic policy makers and world leaders. There is the further challenge of achieving a just decline in the world economy's material throughput that protects the poorest and most vulnerable from its impacts. More practical and promising is the adoption of an "a-growth" macroeconomic perspective and policy, i.e., being indifferent or neutral about economic growth [106]. Ecological economists argue that the promotion and adoption of agrowth could more likely receive political and policy support compared to degrowth since it would allow for economic activity that would be measured as growth to continue in areas of extreme poverty. Meanwhile, conditions of no growth or degrowth, if measured at all, could occur by policy choice in wealthier and more advanced economies [107–109].

Justice concerns could be addressed in a world of growth indifference combined with curtailments on material throughput by adoption of a universal basic income (UBI) in countries and regions that have been experiencing growing and high levels of income inequality [110]. Economic growth has historically served as an indicator of improved well-being despite concerns that one's desire for more well-being may never be satiated through growth [111,112].

UBI can provide evidence of improvement in the well-being of the poorest people, replacing the indicator of positive economic growth while opening up policy space to reduce material throughput in the economy.

All 3 of the debates summarized here occur in policy-relevant areas. The concepts can and have informed legislation and rulemaking on ecological protection and societal well-being [113–115]. For example, the prospectus of first US National Nature Assessment (NNA1) notes that the "four NNA1 themes (conservation and natural resources management, economic interests, human health and well-being, and safety and security) each include questions that address aspects of equity and the fair and just distribution of nature's benefits," topics considered part of "environmental justice" [116] and embedded in the agrowth/degrowth and substitutability debates. While also distinguishing the field from other branches of economics, they illustrate the breadth of ecological economics ranging from basic to applied research.

5. Sustainability and transformation in an ecologically constrained, wealth-concentrated world

Ecological economics provides an opportunity for alternative intellectual directions to address the sustainability challenge. The field recognizes that the biophysical realities of planet Earth and the human pursuit of justice should frame and inform the structure and outcomes of the economy. If one takes existing economic organization and throughput as given, and then moves directly to efficiency analysis, one risks continuing the overshoot of biogeophysical limits and the exclusion of large numbers of people from economic improvement even when the overall pie is growing. If one instead begins by considering limits, distribution, and inclusion, it makes sense to move on later to efficiency through market mechanisms as a complementary goal.

As was envisioned by its founders, ecological economics is by necessity a pluralistic, interdisciplinary, and often transdisciplinary field of research. Whether there can even be a "pluralistic discipline" has been debated [13,10], but we conclude that it is possible and necessary. The necessity of pluralism emerges for 3 reasons: addressing research across geographic scales (global to microscopic) and systems (biotic/abiotic/social); the demands imposed by integrating conceptions of justice with ecology and other natural and social sciences, engineering, and industrial ecology; and pursuing research projects spanning from basic to applied/policy relevant. All are important for achieving real progress in societal transformation. More important than methodological exclusivity is an appreciation of the importance of entropy and justice as conceptual launch points and achieving a sustainable scale of the global economy as a necessary implication. Any set of methods that can operate within this framing can be justified, understanding that peer review will be rigorous.

Many of the insights that emerge in ecological economics are not very distant from policy applicability. One can see this passage from basic to applied in the concepts discussed here. "Entropy" is a theoretical concept, but "sustainable scale" moves one much closer to the policy-relevance frontier. Similarly, "justice" resides in the world of philosophy, but its interpretations, such as "capabilities," pushes us again toward recommendations for government action. We therefore suggest the addition of "and Transformation" to its historical moniker of "The Science of Sustainability" to emphasize the capability of ecological economics to meaningfully address the world's pressing environmental problems.

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